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Review

Prospects of Fuel Cell Combined Heat and Power Systems

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Abstract: Combined heat and power (CHP) in a single and integrated device is concurrent or synchronized production of many sources of usable power, typically electric, as well as thermal. Integrating combined heat and power systems in today's energy market will address energy scarcity, global warming, as well as energy-saving problems. This review highlights the system design for fuel cell CHP technologies. Key among the components discussed was the type of fuel cell stack capable of generating the maximum performance of the entire system. The type of fuel processor used was also noted to influence the systemic performance coupled with its longevity. Other components equally discussed was the power electronics. The thermal and water management was also noted to have an effect on the overall efficiency of the system. Carbon dioxide emission reduction, reduction of electricity cost and grid independence, were some notable advantages associated with fueling cell combined heat and power systems. Despite these merits, the high initial capital cost is a key factor impeding its commercialization. It is, therefore, imperative that future research activities are geared towards the development of novel, and cheap, materials for the development of the fuel cell, which will transcend into a total reduction of the entire system. Similarly, robust, systemic designs should equally be an active research direction. Other types of fuel aside, hydrogen should equally be explored. Proper risk assessment strategies and documentation will similarly expand and accelerate the commercialization of this novel technology. Finally, public sensitization of the technology will also make its acceptance and possible competition with existing forms of energy generation feasible. The work, in summary, showed that proton exchange membrane fuel cell (PEM fuel cell) operated at a lower temperature-oriented cogeneration has good efficiency, and is very reliable. The critical issue pertaining to these systems has to do with the complication associated with water treatment. This implies that the balance of the plant would be significantly affected; likewise, the purity of the gas is crucial in the performance of the system. An alternative to these systems is the PEM fuel cell systems operated at higher temperatures.

Keywords: combined heat and power system; PEM fuel cell; optimization; climate change; fossil fuel

1. Introduction

The quest for a paradigm shift from the high dependence of fossil fuel due to its harmful effect on the environment has increased in the last couple of years [1–6]. Factors like unstable fossil commodities prices and the depletion of the ozone layer are key factors encouraging the research community to consider and alternative energy generation medium. Increasing the efficiency of the current technologies through waste heat recovery [7–9] and/or using renewable energy sources, such as geothermal energy [10], solar thermal energy [11], solar PV [12,13], hydro energy [14,15], biomass energy [16,17], and wind energy [18,19], are gaining much attention because of their friendly nature to the environment. The main issue pertaining to the high reliance of energy from renewable sources has to with the intermittency associated with the energy generation process [20,21]. One of the ideal energy carriers particular for stationary purpose is hydrogen [22,23]. Hydrogen is also useful for other applications associated with transportation [23]. Application of hydrogen for these purposes is considered to be very cheap, especially for large scale purposes, as well as in applications for storing energy over a longer period of time [24,25]. Energy density is another added advantage of hydrogen. Promoting renewables in effect via a robust energy storage method foster their growth, which will substantially reduce GHG emissions [26–29]. The advantage of greenhouse gas emission reduction could be noticed in systems that function using hydrogen [29]. For example, hydrogen-based cogeneration systems obtained through natural gas steam reform to supply fuel cells with energy can still minimize carbon emissions, as well as nitrogen oxides (NOx) [30]. No-emission can be accomplished by producing hydrogen via mediums that are renewable. In a fuel cell, fuel's chemical energy is transformed instantly, generating electrical power at such a reasonably good actual energy efficiency of up to approximately 55%, dependent on hydrogen's high heating value (HHV) [31,32].

Several types of fuel cell technology are primarily classified subject to the operating temperature, type of the membrane, fuel, or application [33–41]. Proton exchange membrane fuel cells (PEMFCs) have been widely recognized as promising technologies among the various fuel cell types [42–48]. PEMFCs are ideal for stationary, transportation, and auxiliary purposes [37,49–52].

PEMFCs have several merits over traditional energy systems like starting very fast (less than 30 s) [53–55], relatively lower operational temperature, high electrical energy efficiency, and rapid response [56–59]. It is imperative to recognize that a high quantity of heat energy is also produced due to the proton exchange membrane operation, equivalent to approximately 45–60% of the total energy content of hydrogen [60–62].

Low-temperature fuel cells are designed to function between 60–80 °C to prevent any overheating likely to cause dryness in the cell likely to reduce the overall performance of the cell [63–65]. In order to extend the proton exchange membrane fuel cells lifetime, as well as efficiency, the heat generated should be eliminated.

Considering the amount of heat produced during the operation of a PEMFC, heat recovery from PEMFC systems becomes an interesting concept for increasing the efficiency of the cells, reducing their cost of operation, and providing a novel technique to minimize greenhouse gas emissions. Heat retrieved from PEMFCs could be utilized for low-temperature heating like heating a room and providing hot water in the home, which requires low-grade heat [66–72]. Several researchers have shown that the performance of PEMFC combined heat and power (CHP) configuration will surge up to approximately 60–90% via absorption of the fuel cell heat [73].

The heat produced from the stack of fuel cells can also be retrieved to control the sorption cooling processes [74–76]. In addition, heat obtained from PEMFC stacks was also utilized for improving the metal hydride (MH) canister hydrogen discharge rate, as well as preheating the inlet air. It is similarly ideal for preheating inlet air, as well as hydrogen, particularly during cold conditions [77]. Generally speaking, the perception of waste heat recovery has been mainly utilized for several years [77–79]. Besides that, the ability of waste heat usage is being investigated in fuel cell systems and has received considerable attention from scientists, particularly in recent years, to increase their overall energy conversion efficiency [80–82]. This investigation presents the latest trends in fuel cell combined heat and power, and critically reviews the key parameters impeding their commercialization. Components of fuel cell combined heat and power systems are thoroughly discussed holistically with their merits and demerits clearly ascertained. In this report, the next sections will further explore the classifications of fuel cell combined heat and power based on their operational characteristics, as well as material compositions. This investigation will serve as the basis for future research activities in fuel cell combined heat and power systems. Currently, hydrogen is the commonly used fuel, and it's imperative that other sources of fuel are considered in future investigations. Similarly, optimization of the fuel cell in terms of material characterization will also go a long way to reduce the overall cost of the system; hence, should be an active research direction in future investigations within this field. The systemic design should also be a key research direction, which will impact on the cost of the system, as well as modularity. A well-documented and robust risk assessment strategy should critically be looked into in future works. Finally, public sensitization on the viability of this novel technology will also accelerate its commercialization and possible competition with existing forms of energy generation.

2. Fuel Cell Combined Heat and Power Systems

Fuel cell operates via electrolytic medium purposely for transforming chemical energy of hydrogen, as well as oxygen to power. The byproduct of the electrochemical reaction is water and heat [57,83]. Operating theory resembles that of batteries, but then provides constant energy, from the hydrogen and oxygen supplied to the cell [84]. Fuel cells are able to generate power, releasing no toxic gases into the atmosphere; production of power in fuel cell occurs silently and requires the fuel cell to be frequently disposed of when the fuel is completely utilized [85,86].

Fuel cells could further possibly be utilized in many applications that demand power. Fuel cells could be utilized by substituting the ICEs or batteries in transport applications and portable applications for generating energy. Fuel cells can equally generate power for residential or industrial purposes.

Fuel processor changes the fuel to hydrogen-rich feed streams like natural gas or methanol. The stack then produces electricity, as well as thermal energy, once the hydrogen gas is supplied to it. The power required by the end-user is obtained using the power conditioning system in the form of non-linear DC voltage. Combined heat and power systems are usually made up of a generator, as well as a heat recovery module, as shown in Figure 1, adapted from Reference [29].

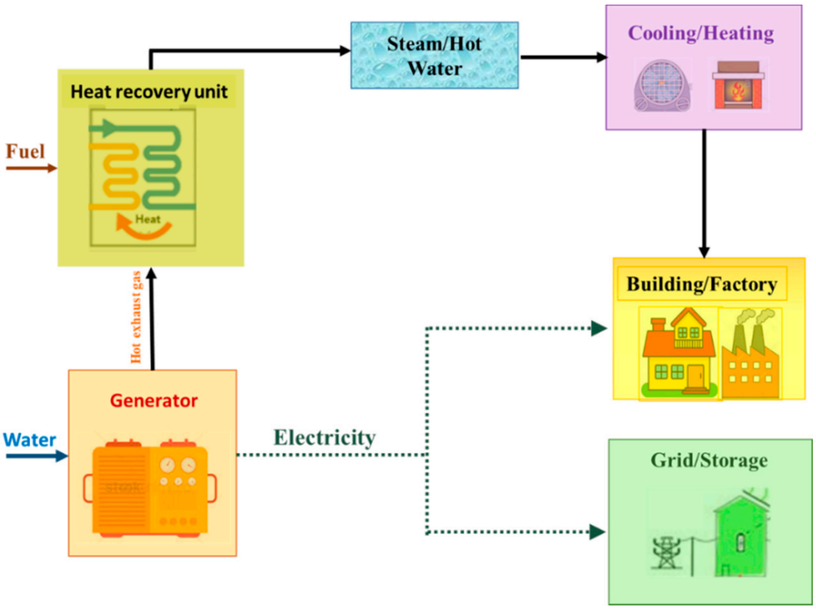

Figure 1. Composition of combined heat and power systems.

A heat exchanger serving as a heat recovery subsystem absorbs the waste heat. The energy that is retained can then be used for heating. Electricity is produced as a result of the generator transforming the chemical energy in the fuel. It is possible to classify cogeneration systems for domestic and industrial institutional applications per their prime mover. Combined heat and power technologies subject to the Stirling engines, as well as fuel cells, are considered to be ideal for cogeneration, especially for household infrastructure. That of the fuel cells is perceived by the research community to have higher efficiency coupled with lower emission levels. Still, presently the cost for internal combustion engines are cheaper compared to the others. Similarly, internal combustion engines can be suitable for combined heat and power systems because they are naturally robust, as well as considered advanced technologies. The microturbine based technologies are ideal for domestic applications [30].

One of the main issues associated with the development of combined heat and power is the challenge relating to the distribution of thermal energy for a longer distance. Due to this, the combined heat and power system must be built near where it is required, and this becomes an extra cost to the system. The fuel cells combined heat and power system have become active research directions because they produce high efficiency for many types of load profiles, as well as low emissions in the absence of any controls. Fuel cells combined heat and power systems achieve greater efficiencies compared to other low-scale power range combined heat and power technologies, which are typical for household uses.

Similarly, for household and industrial areas requiring lower energy (generally less than 10 kW), fuel cell combined heat and power can be used as well. The types of fuel cell combined heat and power based on their power range is captured in Table 1. The heat quality is subject to the fuel cell type used in the system, which directly affects the operating temperatures.

Phosphoric acid fuel cells' electrical output varies from 37% to 42%, and when working in combined heat and power systems can hit approximately 85%. Systemic performance can surge up to 90%, provided the system makes use of the thermal output. As stand-alone power plant, molten carbonate fuel cell can achieve approximately 47% electrical output, and therefore, can achieve an output of 85% in combined heat and power mode.

The 45% electrical output goal is likely to be attainable with high-temperature PEMFC and solid oxide fuel cells (SOFCs), but low-temperature cells may not be able to attain these efficiencies. Only SOFC systems at required electrical efficiency can achieve targeted combined heat and power efficiency of 90%.

It can be deduced from Table 1 that PEMFCs, as well as SOFCs, are the ideal and often utilized fuel cell systems for domestic purposes. Estimated 138,000 fuel cells combined heat and power systems under 1 kW was developed in Japan by 2014 [87]. Many of the developed combined heat and power systems are based on PEMFCs (85%), and remaining systems are based on SOFCs [88].

Elcore and PlugPower are focusing on designing, as well as demonstrating, high temperature combined heat and power systems. Fuel cells have undergone massive development and demonstration in the last five decades; however, fuel cell systems are still immature. The cost of implementing fuel cell combined heat and power systems are also very high, hence impeding their commercialization [89].

Table 1. Classification of fuel cell combined heat and power "FC—CHP" subject to the range of power [29].

Rating	**Megawatt**	**Sub Megawatt-Class**	**Micro Combined Heat and Power**		
Category of fuel cell	MCFCs	PFCs	SOFCs	PEMFCs	SOFCs
Electrical capacity	300 KW–2.8 MW	400 kW	Up to 200 kW	Less than 10 kW	700–1000
Operational temperature	600–700	160–220	700–1000	60–80 100–200	
Electrolyte	Li_2CO_3/K_2CO_3 materials	H_3PO_4	ZrO_2	Nafion Polybenzimidazole electrolytes	ZrO_2
Use	Domestic and industrial purposes	Industrial purposes	Industrial purposes	Domestic and industrial purposes	
Source of hydrogen	CH_4	CH_4	CH_4	CH_4	
Types of fuel that can be used	Hydrogen gas, methane	Hydrogen gas	Hydrogen gas, methane	Hydrogen gas, methanol	Hydrogen gas, methane
Source of oxygen	Pure oxygen gas and air	Pure oxygen gas and air	Pure oxygen gas and air	Pure oxygen gas and air	
Merits	Higher performance can be scaled down, and varying fuel cells are applicable	cogeneration performance is high	Cell performance is high	Higher performance	
Power performance (%)	42–48	40–43	50–65	21–40	40–60
Combine heat and power performance (%)	85	85–90	90	87–90 (low temperature fuel cells) 85–90 (high temperature fuel cell)	90
Combine heat and power applications	Space heating and heating water	heating water	Subject to the technology adopted	Suitable for space heating	
Possible pollutant	Sulfur	Carbon monoxide is less than 1%	Sulfur	Carbon monoxide is less than 10 part per million (low-temperature fuel cell). Carbon monoxide is less than 5 ppm, and only traces of sulfur and ammonia are detected (High-temperature PEMFC).	Sulfur

3. Technological Advancement for a Combined Heat and Power System

Fuel cells are starting to gain significant market share, and in the last decade, have switched from the research laboratories to the industrial showroom. Table 2 displays commercially available fuel cell micro (m) combined heat and power devices available on the market. The combined heat and power systems market keeps increasing appreciable over the last couple of years, but there is a huge difference between existing technologies, and these combined heat and power systems [90].

Table 2. Commercially available fuel cell combined heat and power [90].

Production Company	Name of Product	Category of Cell Used	Power Generated (W)
Ceramic fuel cells	BlueGen	Solid oxide fuel cell	1500
Panasonic	ENE-FARM	PEMFCs operated at lower temperatures	250–750
Toshiba	ENE-FARM	PEMFCs operated at lower temperatures	250–700
EneosCellTech	ENE-FARM	PEMFCs operated at lower temperatures	250–700
Kyocera	ENE-FARM	SOFCs	200–700
Aisin Seiki	ENE-FARM	SOFCs	200–700
JxEneos	ENE-FARM	SOFCs	250–700

As depicted in Figure 2, the fuel cell combined heat and power systems keep increasing appreciably worldwide, and these values have increased twice-yearly [91]. For instance, the fuel cell commercial shipments increased to 45,700 units as of 2012 [92]. It has been deduced that since 2013, the global market sales for fuel cell combined heat, as well as storage, always exceeded the internal combustion engine system in terms of purchasing capacity. Japan continues to dominate the market share for global fuel cell combined heat and power systems [93]. The Japanese government is nearly meeting its targets in terms of installing 1.4 million fuel cell systems. The basic goal laid down by the South Korean government is to establish a 1 million fuel cell systems, and that of the European Union is 50,000 fuel cells installed.

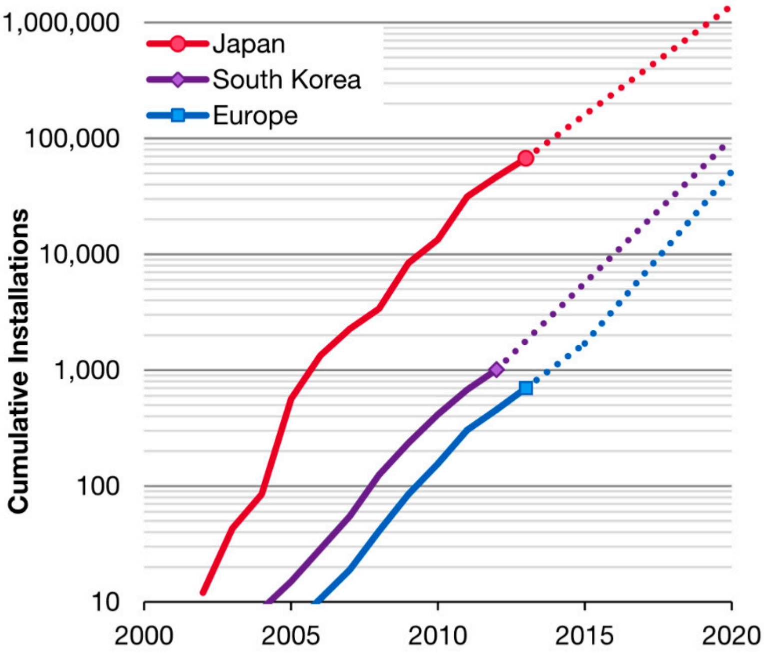

Figure 2. The number of residential fuel cell micro combined heat and power systems [91].

3.1. Technical Evaluation of Microgeneration and Combined Heat and Power

The production of zero or low carbon heat by small businesses, individuals, and the community, which will supply their own demand is microgeneration. The local generation, for example, can reduce the cost of operation, as well as carbon savings, through the application of renewable energy sources or the retrieval of waste heat, as seen in combined heat and power systems. It curbs the losses relating to producing power through the grid for longer distances. The heat, coupled with power produced, are usually utilized on the spot. Fuel poverty can equally be restrained via lower operating cost, and add to the supply of energy. There are different types of microgeneration that can use the energy already in existence in the environment or produce power, as well as heat from the fuel. The importance of micro combined heat and power in terms of energy-saving is summarized in Figure 3.

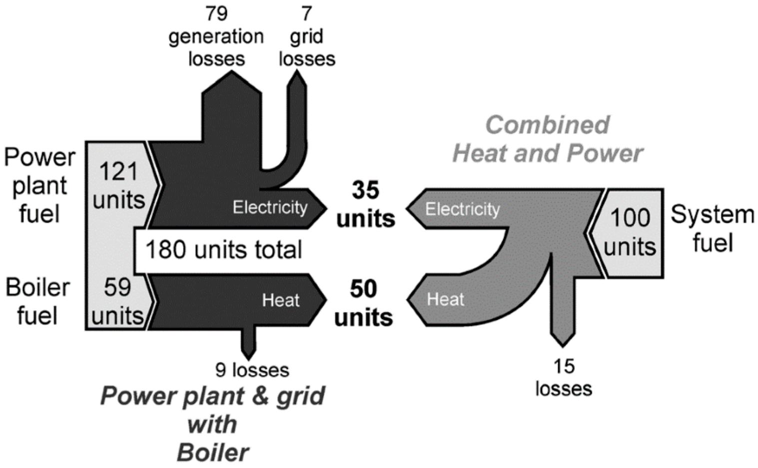

Figure 3. Sankey diagrams capturing the merits associated with producing heat. The performances captured here are descriptive subject to the system, as well as the country [94].

A two Sankey diagrams capturing the benefits associated with micro-combined heat and power systems are captured in Figure 3. The diagram compares the delivery and losses of energy for a house with the aid of micro combined heat power systems instead of relying on thermal power plants. Losses via waste heat liberated and losses relating to the transmission of electricity over a longer distance supports the conventional generation scenario. The distance between the load and the generator determines the transmission losses. There are other factors like the voltage used, as well as the number of voltage transformation stages. The losses vary from 6.1% in Germany to 24.2% in Croatia, and 3% to 13% in the United States [95]. The highest efficiency gas subject to heating is provided by the condensing boiler. Some producers of these boilers suggest their efficiency to be nearly 98%. It has been reported that a seasonal efficiency of 91.5% higher heating value was recorded, while 5% efficiency was recorded from an independent study [96]. Figure 4 (adapted from Reference [94]) shows micro combine heat and power system for domestic application.

The gas distribution network from Figure 4 supports the transmission of natural gas. The fuel cell, on the other hand, generates heat for space, as well as water heating coupled with electricity for the light and other appliances. The electricity is sometimes exported to the grid when it is produced in excess and imported as well when demand is high. A storage tank for hot water is also used for storing excess heat. It is equally possible for them to be operated in places where there no electric grid or even a network for distributing natural gas. In an instance like that battery storage is needed. During situations like this, battery storage is required, and the fuel will be supplied in cylinders. European Union cogeneration directive explains micro combine heat and power systems as being made up of below 50 kW. Other authors similarly restricted these values to 15 kWe, and this is ideal for single-family houses and small business.

The Carbon Trust initiated its micro-combined heat and power accelerator program by explaining that micro combine heat and power systems are between 0–3 kWe. To be in conformity to the European Union directive, domestic has been added as a prefix. Microgeneration technologies are caped to 16 A/phase when not connected to relays utilized for domestic purposes in the United Kingdom.

Hence applications more than approximately 3.7 kWe need 3—phase G59 relay. This is likely to increase the cost of installation, and line rental [97].

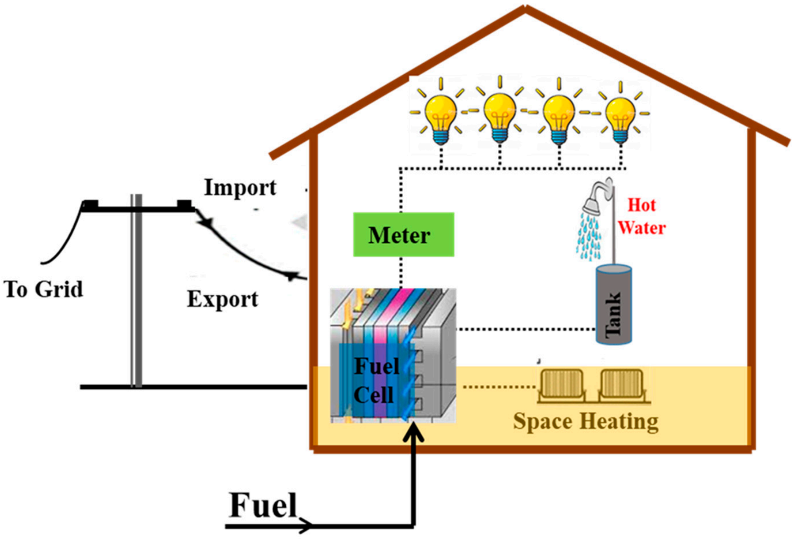

Figure 4. Fuel cell micro combined heat and power (CHP) for importing and exporting electricity.

These types of technologies are not suitable for district heating. This is because district heating demands the presence of heat distribution networks that his not available in single-family homes. There are some limitations created on the units running hours when the thermal output is more than the typical requirement for a single house. Combined heat and power at a larger scale in terms of an economic case is very common, especially for schools, hospitals, industry etc. This industrial sector is considered to be advanced. The challenge occurs when considering the same system for residential purposes. The installation of micro combined heat and power is likely to decrease overall emissions by 15–20%. According to Carbon trust, these values were marginal for some micro combine heat and power systems [96].

Figure 5 above depicts a generic fuel cell system for domestic micro combined heat and power systems. The next section will explore the composition of the various elements in the system.

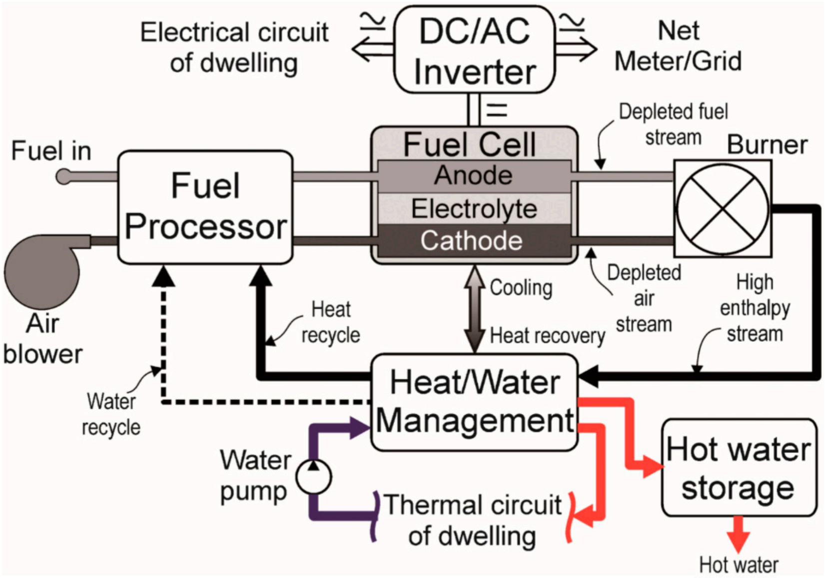

Figure 5. The schematic diagram for fuel cell micro CHP systems [94].

3.1.1. Fuel Cell Stack

Fuel cell stack is the costliest part of the system. It is made up of cells connected in series. The cell stack is made up of an anodic and cathodic electrode with an electrolyte serving as a barrier between the electrode. Bipolar plates support the dissemination of the reactants to the electrodes [98]. The proton exchange membrane fuel cells normally have cooling plates for demineralized water, but the SOFCs depends on air, reducing the cell operating temperature. Precious metal electrocatalysts are needed in PEMFCs to speed up chemical reactions for higher cell efficiency. This often requires graphite powders and resins being used. Other researchers have equally explored the application of membranes that are fluorinated. To ensure the higher performance of the cell, the purity of the hydrogen fuel must be very high because the electrocatalyst can become contaminated by carbon monoxide, as well as other impurities [99]. Humidification of the polymer electrolyte demands complex and expensive engineering solutions.

Recent investigations are aimed at increasing the operating temperature beyond 100 °C [100]. Solid oxide fuel cells utilize ceramics to support their higher cell operating conditions [101]. For micro combined heat and power systems, there is currently an effort to go from the high-temperature region (850–1000 °C) to intermediate temperatures range between 500–750 [102]. It accounts for a wider variety of materials that can be utilized, allowing inexpensive processing and enhanced resilience between ambient and operating temperatures for cycling ceramic components. Operating the cell at lower conditions equally supports the cell to be able to start operation very fast. The rate of corrosion of the metallic part in the cell is also reduced [102]. Pressuring the reactants is likely to enhance the performance of the fuel.

3.1.2. Fuel Processor

In terms of electrochemical efficiency and longevity, hydrogen is a suitable fuel for all types of fuel cells. Similarly, due to lack of supply infrastructure, as well as difficulty in its storage, natural gas is considered as excellent fuel for combined heat and power systems. Methane gas is inexpensive and readily available, hence its patronage. Fuel processors are designed to transform the methane gas, for instance, to hydrogen with low contaminants.

The key distinction between PEMFC and SOFC systems is in the fuel processor design; while the PEMFCs need higher purity fuel, the solid oxide is able to reform hydrocarbon fuels internally. Typically, a solid oxide fuel processor consists of a desulfurizer, and a pre-reformer. SOFCs ability to operate on hydrocarbon fuels at high efficiency is a massive benefit over low-temperature fuel cells [103].

Natural gas is capable of being transformed into hydrogen through a variety of methods. Steam reforming is usually recommended as it generates better hydrogen concentrations [104]. The hydrogen-rich stream that leaves the reformer will be made up of carbon monoxide, as well as sulfur compounds. Both molecules are toxic to PEMFCs, although SOFCs are capable of using carbon monoxide as a fuel. Therefore, sulfur compounds should be eliminated, typically by reacting with zinc oxide. The unit will have to be regularly checked. This, therefore, becomes an extra cost to the system maintenance costs.

Other methods of desulfurization are available. The majority of these techniques are not appropriate for usage in some applications on a small scale [105]. For proton exchange membrane fuel cells, to avoid poisoning the platinum-based anode electrocatalyst, the level of carbon monoxide accessing the fuel cell must be reduced to the order of less than 100 ppm. Carbon monoxide generated during the process of steam reforming can subsequently be transformed into carbon dioxide in a shift reactor.

Methods, such as selective carbon monoxide oxidation, could be utilized to decrease the concentration of carbon monoxide to safe proton exchange membrane levels [106]. Consequently, the fuel processor for a proton exchange membrane fuel cell is quite complex and needs good temperature control. Above all, the turndown ratio is mostly affected since maintenance of thermal homogeneity remains a considerable problem. Solid oxide fuel cell systems have a strong benefit over proton exchange membrane fuel cell systems, as they are able to change hydrocarbons entirely internally.

3.1.3. Inverter/Power Electronics

For a 1 kWe system, the voltage generated by the stack is low. There is also high direct current (DC) output, usually more than 15 V to a maximum of 40 V. Therefore, it requires an inverter to transform this into alternating current appropriate for other devices, as well as being sold to the grid. The inverter performance is normally between 85–95% at the sub-10 kW level [107].

3.1.4. Water Management

Steam reforming, as well as ensuring proper water management in the cell, will require high purity water to support the conduction of the protons. Heat exchanger removes water from stack exit, harvest heat, and provide process water, which can be utilized for steam reforming or for proton exchange membrane fuel cell water management.

3.1.5. Heat Management

Efficient heat retrieval is crucial for a micro-combined heat and power system's environmental and economic performance. There is significantly different heat separation from the PEMFCs, as well as that from the solid oxide systems. Heat is normally derived from the circulating cooling liquid for the PEMFCs, which moves via the cooling plates. This leaves the stack at 80 °C approximately, an optimal temperature for heating up room and hot water.

Coolant for the stack is the cathode air flow for SOFCs and requires a heavily over-stochiometric amount of air. The air and unconsumed fuel end up leaving the stack at its operating temperature, as well as heated up in the afterburner. Given that exhaust stream temperature is more than that of proton exchange membrane fuel cells cooling circuit (around 80 °C), transfer of heat to the dwelling's thermal circuit is much more efficient. It is worth noting that both an afterburner and an abstract higher temperature heat from unused fuel exiting the fuel cell may also be used by the proton exchange membrane fuel cell.

3.1.6. System for Delivering the Reactants

As all micro combined heat and power systems are not pressurized, blower instead of the compressor is utilized to deliver air to the machine. The mains gas pressure entering a home, and of course the tanked storage pressure, is necessary to supply a micro-CHP system. The high-temperature operation of solid oxide fuel cells implies preheating of the fuel, as well as air approaching the stack to a degree, which prevents thermal shock to the stack's ceramic portion. Fuel cell producing no noise during its operation is considered as an advantage.

3.1.7. Afterburner/Auxiliary Burner

Heat energy could be produced with the aid of an auxiliary burner via the burning of unreacted fuel. It is a choice for adjusting the system's heat-to-power ratio. At the maximum, the stack can be fully bypassed. This would imply an over-sizing burner as opposed to regular combined heat and power operation, increasing the cost. For PEMFC, adequate heat is needed for serving the fuel processor's endothermic reforming level. Likewise (or moreover) CH_4 could be directly combusted to serve the reformer [108]. In the worst-case scenario, the stack of fuel cells can be completely avoided. For PEMFCs, sufficient heat is needed to serve the fuel processor's endothermal reforming level, so the stack must operate with a fuel usage of no more than approximately 70% to burn the unused hydrogen and serve the reformer.

3.2. Summary of Merits of Fuel Cell Combined Heat and Power Systems

3.2.1. Carbon Dioxide Emission Reduction

Global total carbon dioxide emissions in 2018 increased by 1.7%, which is 33.1 Gt carbon dioxide. This was as a result of the increasing power demand largely generated from fossil commodities. The emissions from this sector are anticipated to continue to rise to 37 Gt in 2035 [109]. A substantial share of greenhouse gas toxic gaseous release increased as a result of higher demand for coal [110]. The growth and development of combined heat and power systems could decrease carbon dioxide release into the atmosphere from the new generation by more than 4% (170 Mt/year), although the saving may boost to more than 10% (950 Mt/year) in 2030 [111]. Therefore, combined heat and power systems can make a significant contribution to achieving emission stabilization, which is needed to avoid major climate disruption. Crucially, combined heat and power near-term emission cuts are achievable, and hence, can provide major chances for low cost greenhouse gas emission decrement [112]. Yearly carbon dioxide emissions reductions are hard to determine.

It is anticipated that residential fuel cell combined heat and power systems of about 1 kW will decrease domestic gaseous release into the atmosphere by 1.3–1.9 tons of carbon dioxide yearly in Japan and Germany. Fuel cells combined heat and power producer CFCL reports to save around 3tonnes per year because of its larger capacity on its BlueGen [112]. A fuel cell and micro combined heat and power systems having an electrical output of 1 kW can produce daily savings estimated at 4.5+ kg carbon dioxide in winter, and 3+ kg carbon dioxide in the summer. The total carbon emissions annually subject to the performance of PEMFCs in UK home has been compared to traditional heating systems as captured in Figure 6 [113]. It was, however, deduced that for a country that relies on coal-fired power, the yearly carbon savings from the fuel cell is likely to be higher [114–116]. Residential proton exchange membrane fuel cells produce 553 g of carbon dioxide to generate 1 kWh of power and 1.4 kWh of heat [116]. The fuel processor is the source for the emission of carbon dioxide. The fuel processor splits the hydrocarbon fuel to hydrogen gas, carbon dioxide, as well as other impurities, with few amounts of fuel being produced for the generation of heat required for reforming.

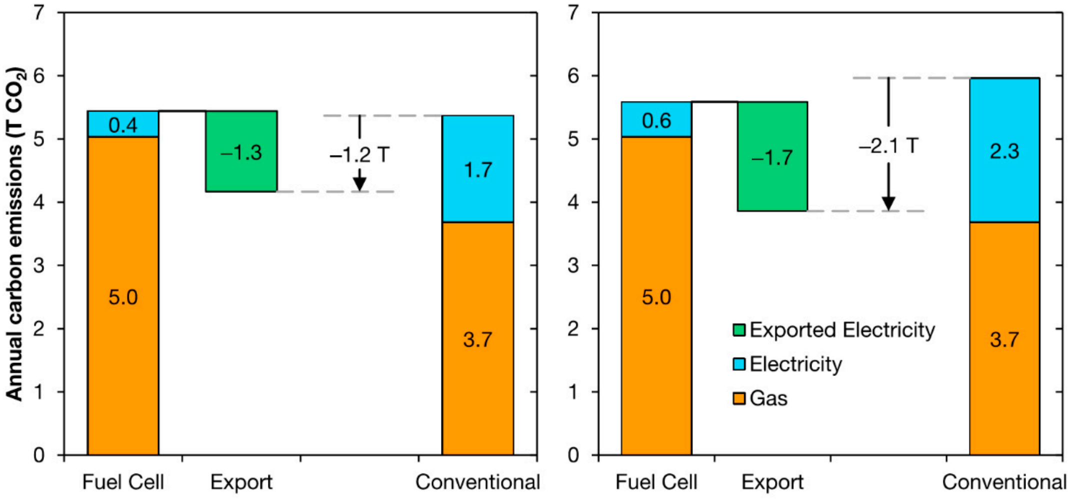

Figure 6. Yearly carbon emission for a UK household [113].

3.2.2. Carbon Footprint for Construction

A fuel cell's 'carbon footprint' or 'embodied carbon' is a measure of the greenhouse gas emissions which its development causes. Various assessments approximated these toxic gaseous release by taking into account the manufacturing of the fuel cell, the quantity of material used, as well as the production process of the materials. The production of metals, such as nickel and platinum, requires lots of energy. The generation of 1 kW of power for domestic purposes using fuel cell combined heat and power will also lead to the production of 0.5–1 tons of carbon dioxide emissions. On the other hand, 100 kW commercial system leads to 25–100 tons being emitted [117–119]. The toxic gaseous release from manufacturing the cell can be 'levelized' by averaging. The development of domestic proton exchange membrane fuel cells, as well as solid oxide fuel cells, results in the gaseous release of 10–20 g of carbon dioxide for every kW generated [118–121].

3.2.3. Decrease in Pollutant

Combustion of fossil fuel usually leads to the emission of many toxic substances into the atmosphere, such as nitrogen oxides (NO_x), as well as sulfur dioxide (SO_2). Sulfur dioxide emissions are from the production of energy, and this, according to literature, contributes to more than 40% of the total emissions gathered annually [122]. Sulfur dioxide emissions are usually associated with the combustion of coal and diesel fuel, but nitrous oxide pollutants are generated from the combustion of different types of fuels.

These types of emissions tend to have a detrimental effect on the environment like causing acid rain. In terms of power generating methods for the fuel cell, the amount of gaseous toxic substances produced in the fuel cell are few. For combined heat and power systems, pollutions due to the presence of nitrous oxide is few compared to that of coal-fired electricity production mediums. Nitrous gas emissions from diesel engines are usually between 1.27–15 kg MWh^{-1}. For natural gas, nitrous gas emissions are between 1–12.7 kg MWh^{-1}. Microturbine engines, on the other hand, also generate 0.18–1 kg MWh^{-1}, as well as for fuel cell combined heat and power; they are lower than 0.01 kg MWh^{-1} [122,123]. Emissions of nitrous oxide source from fuel cell combined heat and power is simply a burner responsible for the supply of thermal energy mainly for endothermic reaction to occur due to the burning of the gas. Various types of burner development have been explored to limit the total gaseous toxic substances generated. There is also the possibility for methane emissions due to incomplete burning or leakage, as well as losses due to gas transport. The emission of sulfur dioxide, as well as mercury compounds from the combustion of natural gas, can be neglected. Sulfur dioxide emissions are removed during the operation of fuel cell combined heat and power [124–126].

The average industrial level for airborne pollutants like nitrous oxide, carbon mono oxide, as well as particulates from the fuel cells, boilers, and combined heat power engines, are summarized in Table 3. Measuring the emissions from fuel cells are always lower compared to other combustion technologies, hence their huge recommendation by the research community.

Table 3. Emissions from fuel cells in comparison to condensing boilers and combined heat and power engines [124,125].

	Fuel Cells	Condensing Boiler	Combine Heat and Power Engines
Nitrous oxide	1–4	58	30–270
Carbon monoxide	1–8	43	10–50
Methane	1–3	13	
Sulphur dioxide	0–2	2	

3.2.4. Reduction of Electricity Cost

The owner of the household having the micro combined heat and power system, enjoys lots of benefits compared to large energy suppliers. The cost in generating the electricity cost related to subsidies for energy technologies, electrical transmission, as well as the distribution cost through the grid network coupled with the final retail customer all determines the cost of the electricity being generated for the end-user. The cost of electricity in Europe varies between £0.087–0. 298 per kWh for households having their consumption between 2500–5000 kWh [127]. The economic value for the energy generated from fuel cell combined heat and power systems tend to have higher economic value. This is 3–3.5 times more compared to power plants powered using natural gas. Fuel cell combined heat and power transforms lower cost of fuel. This helps in reducing the bills in most households.

The efficiency of the power produced in the power plant is between 35–37%. Combine the efficiency of nearly 45% is recorded for centralized power generation. Cogeneration systems can attain performance levels of 80%. Distribution, coupled with the transmission of electricity from the central power stations, add an extra loss of 9%. It implies that the end-user gets one—third of the power supplied. Distribution, as well as transmission losses, therefore, varies subject to distances. From the world data, transmitting electricity and losses associated with distributing the power varies between 1.82–54.60%, with an average of 8.10% [128].

3.2.5. Grid Independence

There has been an appreciable increase in the market potential for fuel cell systems, hence recommended widely by scientists as suitable for solving grid outages. From the United states statistics, 80–90% of energy fiasco comes during the process of distributing the power [129]. The cost associated with these electricity failures is projected to $119 billion annually. More than 45, 000 end-users are affected during these power outages [130]. Failure is associated with some computers, as well as electronic devices, in power fluctuations contributes to power outages. The prices of the yearly cost of power failure linked small industrial structure is summed up in Table 4 [130]. Price for these power cuts varies between $4000–6800 USD.

Table 4. Cost of 100 kWh small industrial structure [130].

Power Failure	Time	Time Facility Stopped	Failure Numbers in the Year	Interruptions Created Yearly	Price Estimate US$	Annual Estimate US$
Brief interruptions	5.3 s	15 min	5	1 h	4000	4000
Extensive time interruption	1 h	2 h	1	2 h	4000	8000
Total			5	3 h		12,000

4. Challenges Associated to Fuel Cell Combined Heat and Power Systems

The main challenge associated with fuel cell combined heat and power system is the high initial capital required for the development of the project, compared with competing with other existing combined heat and power generation technologies. The selection of combined heat and power technology is associated with the cost of generation and system availability. The number of combined heat power units sold is low, but most fuel cell systems for portable applications enjoy huge government subsidies, hence their patronage compared to other combined heat and power systems [131]. The original price for fuel cell combined micro heat and power system is nearly 30–50 times more than the targets laid down by the United States Department of Energy. The cost of 1 kW PEMFCs or SOFCs in Japan was between $21,000–27000 USD.

The cost of the residential system has declined massively in the last decade. In Japan, government subsidy forms nearly 50% of the price for installing the unit. The cost of the system can decrease significantly with respect to time, but this is subject to the economies of scale provided due to producing them in larger quantities. Figure 7 summarizes the cost in terms of reduction for proton exchange membrane fuel cells in Japan and South Korea.

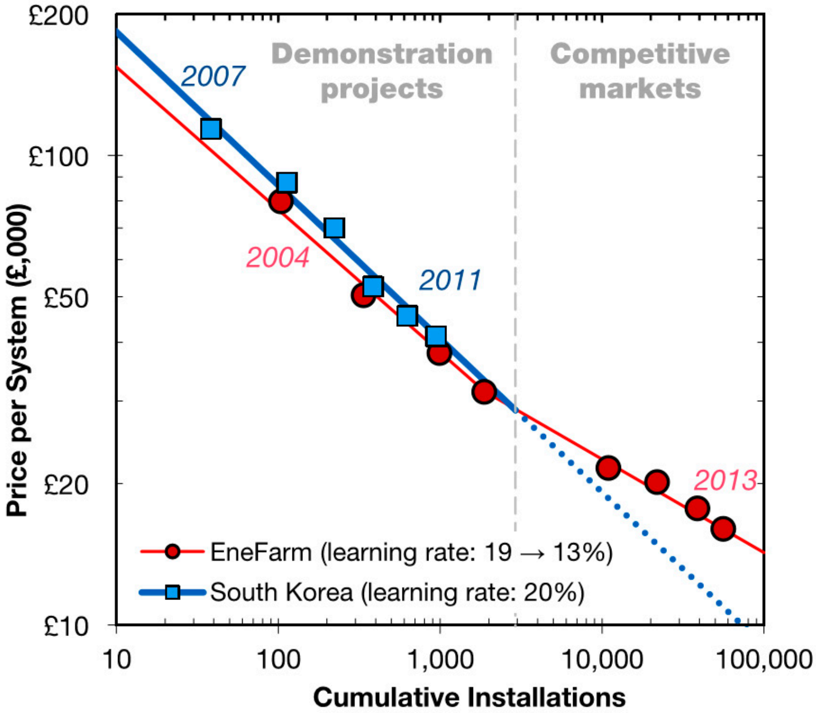

Figure 7. PEMFCs system cost for domestic purposes [132].

5. Conclusions

Micro-CHP systems are appealing, high-efficiency technologies for decentralized electric power generation. This investigation explores and focuses on micro fuel cell combined heat and power systems. Fuel cell combined heat and power has become the most beneficial and effective cogeneration technology. The system has many strengths that can overcome current power generation problems, but it comes with some challenges.

The main drawback at the moment is the initial capital cost, which is expensive. In several demonstration projects, the Japanese scenario demonstrates that it is imperative to reduce the price of fuel cell combined heat and power systems by approximately 25% by doubling the output, and a further 13% reduction after commercialization can be obtained. Several countries are formulating policies, for example, through the implementation of subsidies, which encourage and enhance the applications of fuel cells combined heat and power systems.

Most research activities are geared towards the goals of manufacturing thousands (1000's) of fuel cell combined heat and power systems worldwide for development and deployment. From techno-economic evaluation and energy needs, the appropriate and directed market for fuel cell combined heat and power systems is for domestic purposes, where units up to 1 kWel of power may be utilized for electric power and heat production.

These two fuel cell systems (PEMFCs and SOFCs) are at the moment being used for residential applications in fuel cell combined heat and power systems. SOFCs offer high-quality, high-temperature heat operation. The main issues associated with SOFCs have to do with the time it takes for it to start. Low-temperature PEMFC-oriented cogeneration systems exhibit quite high efficiencies and reliability. The low-temperature PEMFC high power density is undoubtedly the biggest benefit; however, one of the key challenges is the complicated water management. It is imperative that future research work keenly considered novel systemic designs that will make the entire unit very robust in terms of size and weight to reduce the cost of the system. Material characterization and optimization of the fuel cell will significantly reduce the initial capital cost required for establishing such projects. Furthermore, to foster healthy competition with existing technologies, a well-documented risk assessment strategy for the individual components and the entire system, coupled with effective public sensitization about the validity of the technology should be an active research direction.

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